NOSTOS: a spherical TPC to detect low energy neutrinos

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Abstract. A novel low-energy ($\sim$few keV) neutrino-oscillation experiment NOSTOS, combining a strong tritium source and a high pressure spherical Time Projection Chamber (TPC) detector 10 m in radius has been recently proposed. The oscillation of neutrinos of such energies occurs within the size of the detector itself, potentially allowing for a very precise (and rather systematics-free) measure of the oscillation parameters, in particular, of the smaller mixing angle θ_{13}, which value could be determined for the first time. This detector could also be sensitive to the neutrino magnetic moment and be capable of accurately measure the Weinberg angle at low energy. The same apparatus, filled with high pressure Xenon, exhibits a high sensitivity as a Super Nova neutrino detector with extra galactic sensitivity. The outstanding benefits of the new concept of the spherical TPC will be presented, as well as the issues to be demonstrated in the near future by an ongoing R&D. The very first results of small prototype in operation in Saclay are shown.

INTRODUCTION

Nowadays there is a compelling evidence that neutrinos change flavor as they propagate. Appearance or disappearance of neutrinos has been solidly proved in experiments looking at neutrinos of either extraterrestrial [1] (solar and atmospheric) or terrestrial [3] (reactor or accelerator) origin. The neutrino mixing, which provokes the oscillation of the flavor change probability along the propagation of the neutrino, is invoked to explain the observed appearance or disappearance.

The atmospheric neutrino oscillation data [1, 2] strongly suggest that ν_μ oscillate into ν_τ with maximal mixing angle ($\theta_{\rm atm} \sim \pi/2$) and a corresponding mass squared difference of $\Delta m_{23}^2 \simeq 3 \times 10^{-3} eV^2$. Results from accelerator neutrinos support this interpretation [3]. On the other hand, the solar neutrino data [4, 5, 6] could be explained by an oscillation of ν_e into ν_μ and/or ν_τ with a non maximal –but large– mixing angle ($\theta_\odot \sim \pi/3$) and a mass squared difference of $\delta m_{21}^2 \simeq 7 \times 10^{-5} eV^2$, which has been recently supported by evidence of disappearance of reactor antineutrinos [7]. The third mixing angle completing the standard three neutrino oscillation scheme is not known but it is constrained to be quite small $\theta_{13} < \pi/6$ [9]. The determination of this parameter is the remaining question to complete our understanding of the leptonic mixing and, moreover, it will open the way to study the CP-violating effects in the neutrino sector [9].

Such small mixing angle could have measurable consequences in experiments involving electron neutrinos but sensitive to the oscillation length driven by the large squared-mass gap Δm_{23}^2, i.e., the smaller oscillation length. In fact, for a detector close enough to the neutrino source the contribution from the larger oscillation length to the disappearance oscillation probability is negligible, and therefore it is driven only by θ_{13} and Δm_{23}^2 in the following way:

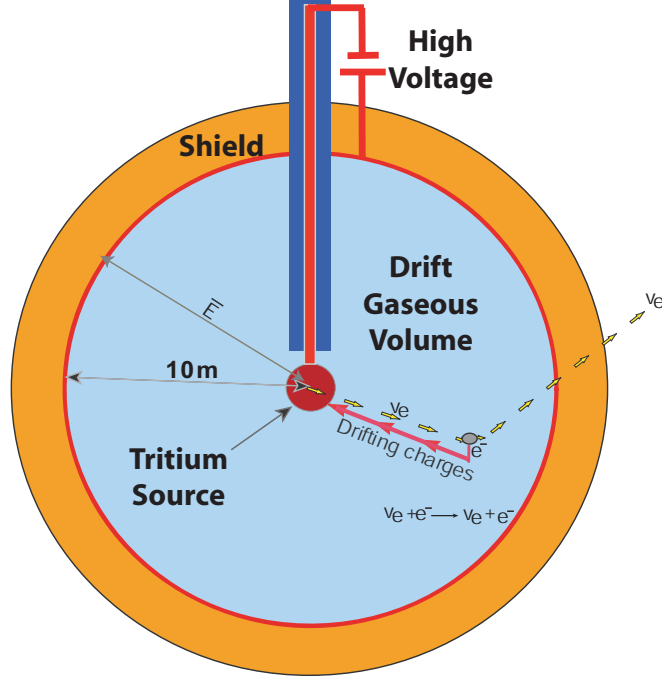[1] attending speaker: Igor.Irastorza@cern.ch

FIGURE 1. Illustration of the proposed NOSTOS experiment, showing the spherical TPC surrounded by an appropriate shield. The neutrino source and the detector are located in the center of the curvature of the sphere. Inside the inner sphere, the tritium source is surrounded by the shield and cooling system and by several Micromegas flat detectors.

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \sin^2 \pi \frac{L}{L_{23}} \qquad (1)$$

where L is the distance between source and observed interaction and L_{23} is the oscillation length related to the neutrino energy E in the way: $L_{23} = 2\pi E_\nu/(\Delta m_{23}^2)$. While for reactor and accelerator neutrinos, this length is of the order of ~ 1 km or ~ 100 km respectively, we want to point out the fact that in the case of very low energy (few keV) neutrinos, like those emitted by a tritium source, the oscillation length L_{23} is only 13 m.

The NOSTOS concept proposes the detection of such low energy neutrinos by using a large spherical TPC of about 10 m in radius, surrounding the tritium source, so the whole oscillation would occur within the detector volume. That could allow the observation, for the first time, of the space oscillating signature and the determination of the smaller neutrino mixing angle θ_{13}, completing our knowledge of the leptonic mixing scheme [8]. The fact that the whole oscillation occurs inside the detector volume allows us to highly reduce systematic effects due to backgrounds or to bad estimates of the neutrino flux, which is the main worry in most neutrino experiments, where the interaction rate is measured at a single space point.

THE NOSTOS DETECTOR: THE SPHERICAL TPC CONCEPT

The NOSTOS principle of detection is based on the concept of the spherical TPC, which has several interesting potential advantages, as will be shown later on. It consist of 2 concentric spheres, the external one, 10 m of radius, at ground and the inner one, 50 cm of radius, at high potential (Fig. 1). The tritium source is located inside the central sphere. Neutrinos escaping radially from the center of the sphere interact in the gas mainly by electron elastic scattering. The ionization charges produced in the interaction drift towards the center and are collected by an adequate gaseous readout, which covers the surface of the inner sphere (possibly composed by a series of flat segments). The preferred choice for the readout devices are Micromesh Gaseous Structures (Micromegas [10]) due to the high precision, fast response and excellent energy resolution. High efficiency for detecting single electrons have been proved with Micromegas [11] even at high pressures [12]. In addition, Micromegas readout is currently being

used for solar axion detection in the CAST experiment [13, 14] where a great stability and ability to reject background events has been achieved.

This novel approach is radically different from all other neutrino oscillation experiments in that the neutrino source and the detector are located in the same vessel; it is then possible to measure the neutrino interactions continuously as a function of the distance source-interaction point, and directly observe the oscillation length that is fully contained in the detector. Indeed we expect a counting rate oscillating from the centre of curvature to the depth of the gas volume, i.e. at first a decrease, then a minimum and finally an increase. Fitting such an observed curve will provide all the relevant parameters of the oscillation by a single experiment.

The radial coordinate of the interaction point is measured by inspecting the time pattern of the charge pulse detected at the center of the sphere which temporal extension is determined by the longitudinal diffusion of the ionization cloud and therefore by the distance drifted. In fact, for our spherical TPC, the electric field at a distance r from the center is given by:

$$E(r) = \frac{R_2 R_1 V_0}{R_2 - R_1} \frac{1}{r^2} \tag{2}$$

where R_1 and R_2 are the inner and outer sphere radius and V_0 is the applied voltage. At low electric fields the drift velocity v_d is roughly proportional to the electric field and the longitudinal diffusion coefficient depends on E as $D_L \sim 1/\sqrt{E}$. Hence the spherical geometry of the electric field enhances the longitudinal dispersion occurred after a given drifted distance r, with respect to the one for a homogeneous field. First calculations show that a precision better than 10 cm, which would largely satisfy the needs of the NOSTOS concept, can easily be achieved. Preliminary results without Micromegas regarding the experimental demonstration of this strategy by the first prototype actually running in Saclay are presented in section 4.

The use of Micromegas will improve those results in two ways. First, the fast pulses then available (rise times of ~ 1 ns) will allow a better measurement of the temporal dispersion of the signal; and second, information from transversal dispersion will in also be available, by means of an appropriate pixelization of the Micromegas readout.

In general, the use of a spherical TPC detection scheme presents the following advantages for the proposed experiment:

- The spherical geometry naturally focuses a large drift volume into a small amplifying detector with only a few read-out channels. It is the most cost-effective way of instrumenting a large detector volume with a minimum of front-end electronics. Such approach simplifies the construction and reduces the cost of the project.
- The placement of the neutrino source in the center of the detector provides a close to 4π acceptance. The spherical detector geometry optimizes the detection efficiency per unit of volume for a given flux of outgoing neutrinos.
- The spherical drift enhances the relation of longitudinal diffusion with drifted distance, as have been shown above, improving the resolution in the determination of the point of interaction, a key issue of the project.
- The ratio of external surfaces (and therefore external materials) over detector volume is optimized for a spherical geometry, therefore allowing a lower background per unit volume due to external surface or material contaminations. In addition, in a spherical geometry the thickness of material needed to hold the gas is minimum, further reducing possible sources of background.
- Large drift volumes can be built without the use of a field cage, unlike cylindrical TPCs. In addition, the symmetry of the design and the compact placement of the readout in the center of the sphere may provide a lower sensitivity to electronic noise (in fact, the outer sphere acts as a perfect Faraday cage to the inner electrode).

NOSTOS EXPERIMENTAL CHALLENGES AND EXPECTED SENSITIVITY

The NOSTOS concept relies not only on the detection, for the first time, of very low energy neutrinos from a tritium source, but on the measurement of the expected oscillation in that detection rate along the detector volume. We are confident, given the present status of the TPC technology, and the potential of the spherical TPC concept exposed above, on the feasibility of the project. However, an R&D program to assess each of the experimental key issues on

which the project relies, as well as to experimentally demonstrate them, is already ongoing. The main experimental issues can be summarized as follows:

- **Energy threshold:** Neutrinos from tritium decay have a maximum energy of 18.6 keV, therefore the maximum energy of the recoiling electron is of only 1.27 keV. An energy threshold of the order of ~ 100 eV is desirable to have a good sensitivity. Single electron efficiency has been achieved by Micromegas readout devices [11], but low threshold operation with large volumes like that of NOSTOS is being checked experimentally, as part of the ongoing development phase.

- **Background:** Although absence of background is not a requisite for the NOSTOS scheme, as runs without the source can be performed to determine the background, it is true that the presence of a given level of background will decrease the sensitivity of the experiment. As a first measure, the experiment should be located underground. In addition, studies are ongoing to determine precisely the loss in sensitivity for a given level of background, in order to assess to which extent are low background techniques necessary, including shielding, vetoing, material radiopurity and gas purification, as well as offline rejection techniques. Ultimately, an experimental test in underground location with a prototype is envisioned to prove that the necessary low background level can actually be obtained.

- **Radial resolution:** The determination of the radial coordinate of the interaction point through the measurement of the time dispersion of the detected charge pulse is a key issue of the NOSTOS concept. Preliminary results concerning this point have been already obtained with the prototype detector which is not equipped with Micromegas and will be presented in the next section. Work is in progress to assess the final radial resolution achievable.

- **Scaling up:** Finally, even if good experimental parameters are demonstrated for small prototypes, work has to be done to assure that they will be maintained after the scaling up to the full size required by the NOSTOS experiment. To this end, an intermediate scale (4 m diameter) prototype is being designed and will be used in a second stage of the ongoing development phase.

- **Electrostatics:** Right now, a metallic rod supports the central sphere. This provokes a distortion of the electric field, so that only a third of the volume (opposite to the stick) is reasonable close to the desired spherical field of (2). Two main ideas are being considered to solve this problem:
  - **a)** Use of field shaping rings along the metallic rod at corresponding potentials. The extremity of the rod, next to the small sphere, would be made of a resistive cone.
  - **b)** A charging system like the one used in electrostatic accelerators, using a series of small metallic balls on an insulator chain. Due to the absence of beam discharging the "terminal", a very small chain would be sufficient.

Using a 20 kg tritium source (=200 MCi) the total number of emitted neutrinos is $6 \times 10^{18} \nu/s$. With the TPC filled with Xe at 1 bar the number of detected neutrinos is about 1000/year, assuming an energy threshold of 100 eV. The use of a less intense source or cheaper gases like Ar or Ne is possible at the expense of operation at higher pressures. High pressure TPC with Micromegas readout have been successfully tested [12] in the past. They are included in the NOSTOS development program in order to study the viability of such mode of operation.

A detailed study based on Monte Carlo simulations with realistic experimental parameters and with the rigorous treatment of the neutrino interaction including atomic effects developed in [15] is currently under way in order to determine more precisely the sensitivity prospects of this proposal.

PRELIMINARY RESULTS FROM THE FIRST SPHERICAL PROTOTYPE WITH A NEW PROPORTIONAL COUNTER

A prototype of spherical TPC has been built as a first step towards the NOSTOS detector, and is currently being used at Saclay to perform demonstration tests. The spherical vessel is 1.3 m of diameter and is made of 6 mm thick copper, allowing to hold up to 5 bar of pressure. The first tests were oriented to the assessment of the tightness of the vessel, so the gas could keep the sufficient level of purity for right operation. The volume was pumped by a primary pump followed by a turbo molecular pump, reaching a level of vacuum below 10^{-6} mbar. The outgassing rate measured was below 10^{-9} mbar/s, which allows us to avoid permanent gas circulation through special cleaning filters and to operate instead in seal mode.
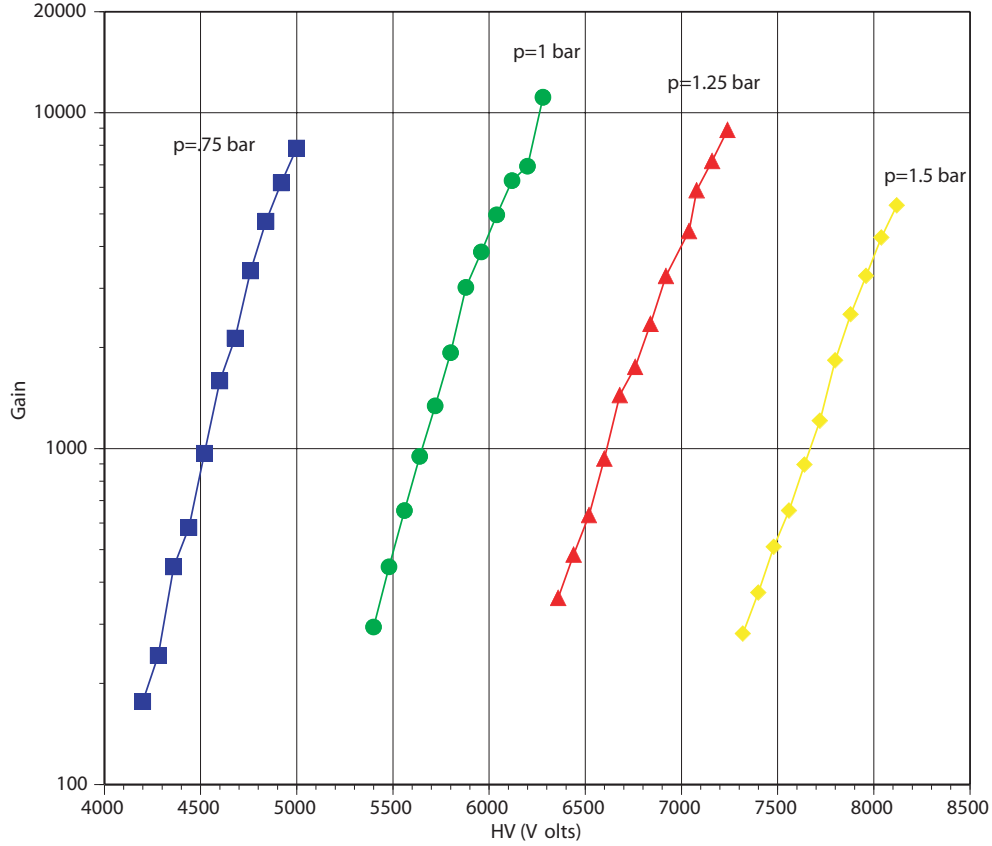
FIGURE 2. Measured gain as a function of the voltage applied, for Ar + 2% Isobutane at four different pressures.

As mentioned before, a Micromegas-type readout is proposed as amplification structure in the center of the TPC. Work is in progress to actually design and build a spherical Micromegas detector with new technologies. A more conventional alternative would be to approximate the spherical geometry by a composition of several flat Micromegas elements. While working independently in the design of the amplification structure, the first tests with the spherical vessel were performed using a small spherical electrode (10 mm diameter) placed in the center of the TPC, working as a proportional counter. The signals from this proportional counter are very slow, for only the ion movement can be observed, and their path is long. The use of Micromegas, where the electron movement in the 100 μm gap will be observed will lead to much shorter pulses. The system shows a very small capacity, $\sim$1pF, and therefore a very low level of electronic noise is expected ($< 1000e^-$) allowing for a potentially very low threshold.

So far the prototype has been operated with two different gas mixtures, namely Ar + 10% CO_2 as well as Ar + 2% Isobutane; and at different pressures up to 1.5 bar. These first tests showed that even with such a simple amplification element, high gains (above 10^4) are achieved. Figure 2 shows the obtained gain versus voltage curves. Stable operation was tested up to 40 days, without gas circulation (seal mode). This results are very encouraging but we are not yet in the tritium configuration. Runs using calibration sources of ^{109}Cd and ^{55}Fe or cosmic rays have been performed. An example of a ^{55}Fe 5.9 keV event is shown in Fig. 3. The remarkable low noise that the baseline of the pulse of fig. 3 shows that thresholds as low as $\sim$100 eV are already at hand.

To study the drift, the ^{55}Fe source is introduced inside the sphere by means of a movable insulant stick which allows us to place the source at any distance from the inner electrode. Data taken at different source distances show no evidence of loss of signal intensity due to electron attachment. In Figure 4 the recorded energy spectrum of one of these runs is shown.

These data allow the study of the drift properties of the chamber. Preliminarily, no appreciable electron attachment has been observed. The main concern at this point of the development phase is to demonstrate whether the time diffusion of the event can be measured and the drift distance extracted from it. To this end, as long as we do not equip
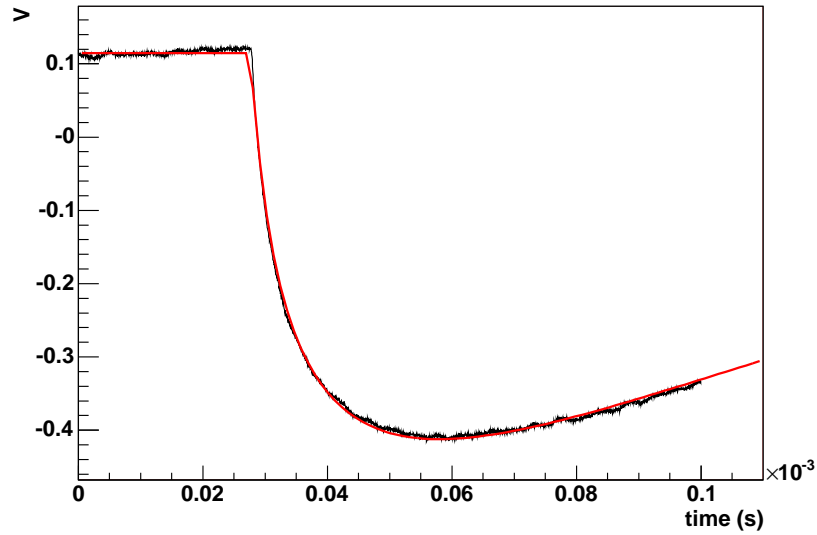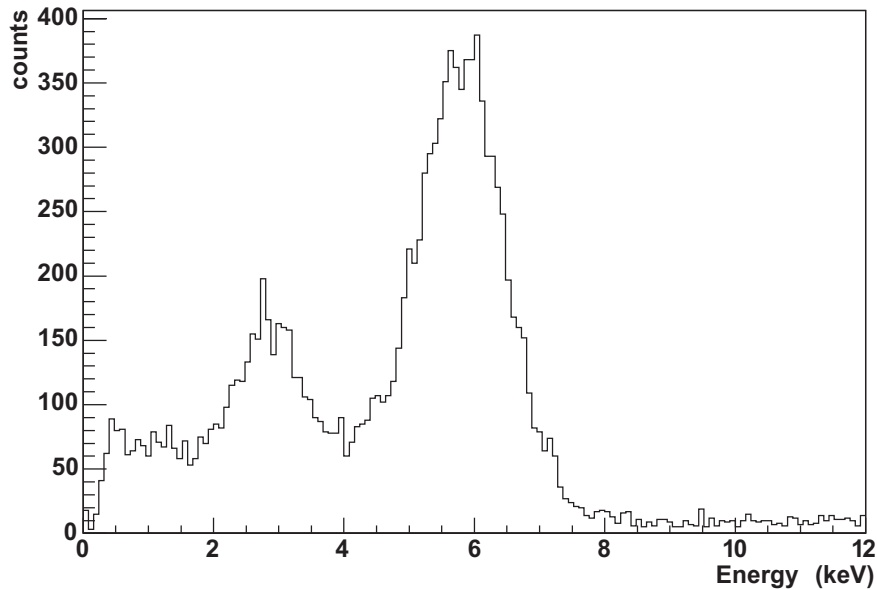
FIGURE 3. Example of a Fe^{55} pulse.

FIGURE 4. ^{55}Fe spectrum.

the anode with Micromegas, a detailed Pulse Shape Analysis is being developed based on deconvolution techniques. Although the work is still under progress, the first results are encouraging, showing that a 10 cm resolution is already achievable as shown in Fig. 5. The technique is supposed to unfold the effect of the electronics and the charge induction from the raw pulse, to arrive to the deconvoluted pulse, a bare reflection of the temporal pattern of the electron cloud arriving at the central electrode. In Fig. 5 various "template pulses", each one obtained by averaging 20 deconvoluted pulses, are shown for different positions of the calibration source. The effect of the diffusion (as the width of the pulse) is clearly visible.

Due to the mean free path of the ^{55}Fe X-rays in the gas, there is an uncertainty in the position of the interactions in those tests. To overcome this difficulty a new way of calibrating this effect is being designed. It consists of the use of
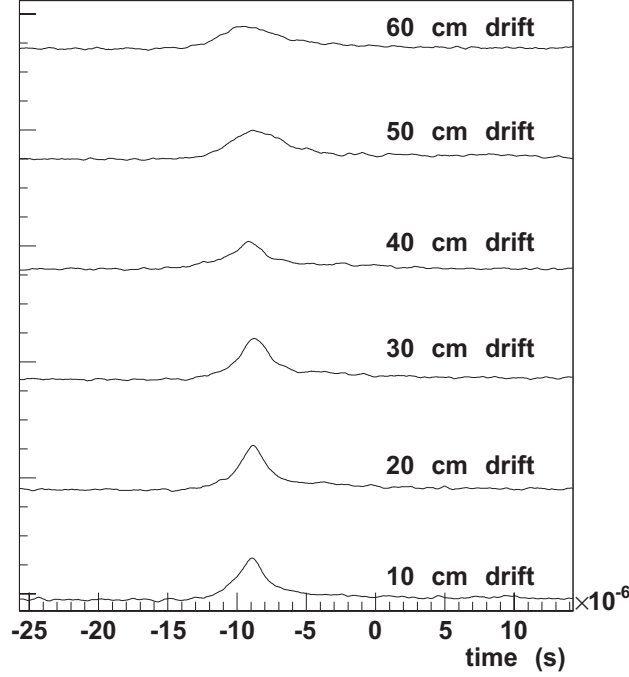
FIGURE 5. Effect of the diffusion on the deconvolved pulses. Each line corresponds to pulses taken with the source at different distances from the inner electrode, from 10 cm up to 60 cm in steps of 10 cm.

a ^{241}Am source, emitting simultaneously an α and a 60 keV γ. The α is detected by a small silicon diode providing the trigger to detect the γ interacting in the sphere. The time delay between the α and the arrival of the electrons at the small sphere provides an accurate measure of the drift time.

ADDITIONAL PHYSICS PROGRAM

We briefly mention some additional application of the NOSTOS detector in the domain of neutrino physics.

Sensitivity to the neutrino magnetic moment

Because of the low energy of the incoming neutrinos and the low energy electron recoils detected in this experiment the sensitivity for the neutrino magnetic moment is high. The cross section of the magnetic moment can be written as[16]:

$$\left(\frac{d\sigma}{dT}\right)_{EM} = \sigma_0 \left(\frac{\mu_l}{10^{-12}\mu_B}\right)^2 \frac{1}{T}\left(1 - \frac{T}{E_\nu}\right) \tag{3}$$

Because of the dependance $1/T$ (T is the electron recoil energy) the sensitivity for the magnetic moment is obviously higher at low energy. Recent measurements from the MUNU experiment [17] show a limit of 10^{-10} μ_B for the neutrino magnetic moment. Our experiment opens the way to improve this value by two orders of magnitude.

Measurement of the Weinberg angle at low energies

Another interesting quantity is the Weinberg angle appearing in standard neutrino cross-sections, which is a function of the momentum transfer and it has not been measured at such low transfers. To this end atomic physics experiments, which utilize the neutral current, have thus far been considered.

By plotting the differential neutrino-electron cross section as a function of the electron energy we obtain a straight line. We hope to construct the straight line quite accurately. Thus we can extract a value of the Weinberg angle both from the slope and the intercept achieving high precision.

Supernova sensitivity. Coherent neutrino scattering

It is generally believed that the core-collapse supernova explosion produces a large number of neutrinos and 99% of the gravitational energy is transformed to neutrinos of all types. The supernova (SN) neutrino flux consists of two main components: a very short (< 10 msec) pulse of ν_e produced in the process of neutronization of the SN matter through the reaction $e + p \rightarrow e + n$, which is followed by a longer (< 10 sec) pulse of thermally produced ν_e, ν_μ, ν_τ, and their antiparticles. Only a small fraction, about 1%, of the neutrinos are prompt, while the rest are neutrino-antineutrino pairs from later cooling reactions. It is expected that spectra of thermally produced neutrinos are characterized by the different mean energies: $\nu_e = 11$ MeV, $\bar{\nu}_e = 16$ MeV, $\nu_{e,\mu} = 25$ MeV. Our idea is to use the large cross section offered by the coherent neutrino-nucleus cross section for detecting neutrinos from Super Nova explosions. Coherent scattering occurs when neutrinos interact with more than one particle and the amplitudes from the various constituants of the target add up. The increase of the cross section is proportional to the square of the number of particles in the target leading to increased counting rates:

$$\sigma = \frac{G^2 N^2 E^2}{4\pi} \tag{4}$$

where G is the weak coupling constant, N is the number of neutrons in the target nucleus and E is the neutrino energy. In order to get advantage of the coherent scattering amplification of heavy nuclei gases are needed.

For instance, using Xenon as detector target the coherent cross sections at E=25 MeV, the energy that is relevant for Supernova detection, is quite large ($\sigma = 1.5 \times 10^{-38}$ cm^2). Even at lower energy (11 MeV) where the coherent cross sections decreases quadratically with energy, the cross section is still high. The recoil energy energy is quite low and it takes a maximum value of 1.5 keV for 11 MeV and 9 keV for 25 MeV neutrinos. This implies that detector thresholds must be set quite low with one advantage that backgrounds are highly suppressed given the narrow time window in which the burst takes place. The collected energy may be even lower by a significant factor (quenching factor) and therefore sub-keV detector threshold is required. For a typical galactic SN explosion the detector used for the tritium experiment (10 m in radius, p=10 bar of Xenon) the number of detected neutrinos will exceed 100,000. A possibility to test the efficiency of detecting coherent neutrino scattering will be the nuclear reactor. The expected number of neutrino interactions in the gas volume, from a typical reactor neutrino flux and spectrum (10^{13} cm^{-2} s^{-1}) using a detector filled with Xenon is about 350/day/Kg[18]. The drawback is the very low energy threshold needed since the maximal recoil energy is 185 eV. Therefore single electron counting is required imposing a high gain operation of the detector (and a measurement of the quenching factor of the ionization produced by the low energy recoils). A 4 m diameter prototype, as foreseen as a later stage of the development phase, would be a perfect tool for this measurement, as it could contain 2000 kg of Xe at 10 bar.

CONCLUSIONS

The NOSTOS proposal aims at the detection of low energy ($\sim$few keV) neutrinos from a strong tritium source, in order to measure the smaller mixing angle θ_{13}. The new concept of the spherical TPC is proposed as principle of detection. The very first results of small prototype in operation in Saclay have been shown.

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